

INTRODUCTION TO PHOTON 2007

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Abstract

The introductory remarks to the conference Photon 2007 organized at the Sorbonne in Paris in July 2007 are presented.

1 Outline

The Photon 2007 conference consists of International Conference on the Structure and Interactions of the Photon (organized since 1994; since 2003 it covered also interactions of the proton) including the 17-th Int. Workshop on Photon-Photon Collisions (with the first Int. Colloquium on Photon-Photon Collisions in Electron-Positron Storage Rings held here in Paris, in 1973) and Int. Workshop on High Energy Photon Linear Collider (included in the PHOTON conference in 2005; first workshop on photon colliders was organized at LBL in 1994).

Let us reflect on a possible content of the Photon 2009. Perhaps it will consist of:

- Int. Conference on the Structure and Interactions of the Photon **and the Proton** with results from HERA, Tevatron, LHC
- 18-th Int. Workshop on Photon-Photon Collisions with final results from LEP and possibly first results from LHC, in particular on the high-energy photon collisions at LHC
- Int. Workshop on High Energy Photon Linear Collider (PLC 2009) covering both the ILC and CLIC options
- Photons in astrophysics.

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Below I will review some topics presented at the Photon2005 conference, with focus on 40th anniversary of the Vector Dominance Model, then open problems and new ideas related to the photon as well as the potential of the Photon Linear Collider will be described.

2 The Photon: its First Hundred Years and the Future

The previous Photon 2005 conference was organized in the Year of Physics and therefore had a special structure: The Centenary and the PHOTON 2005 organized in Warsaw, the PLC 2005 - in Kazimierz (Poland). Below some of review talks, available in the proceedings [2] or the web page [3], are listed:

- R. Struwer - *Einstein's Revolutionary Light-Quantum Hypothesis*
H. Kragh- *Let There Be Light: Cosmic Photons Prior to the Microwave Background Cosmology*
A. Lawrence- *Multiwavelength Universe*
S. Haroche- *The modern version of the Einstein-Bohr Photon Box: exploring the quantum with atoms and photons in a cavity*
J. Schneider- *Research with Free Electron Lasers for Soft and Hard X-rays*
D. Schlatter- *CERN and the physics of the photon and its weak partners*
A. Wagner- *The two faces of the Photon*
D. Gross- *Einstein and the Quest for Unification*
L. Okun- *Photon: History, Mass, Charge*
N. Straumann- *Gauge principle and QED*
E. de Rafael- *QED precision tests*,
and many more reviews on historical aspects of hadronic interaction of photons by P. Zerwas, D. Schildknecht, A. Buras, S. Brodsky, V. Telnov, V. Fadin, I. Ginzburg, and others.

2.1 40 years of VDM

Vector Meson Dominance is a 40-years old, from the Photon 2007 perspective, idea which is still important and useful. As described at PHOTON 2005 by D. Schildknecht [4], S. Sakurai advocated in 1960 to apply the notion of conserved currents, gauge principle and universality of couplings in description of strong interaction. He predicted the existence of vector mesons coupled to the hadronic isospin and hypercharge currents (ρ, ω, ϕ) , which have been then discovered in years 1961-3. The noninvariance of the mass term of vector mesons was ignored temporary.

These vector mesons were "found" even earlier in the description of the formfactors of nucleons. The current-field identity (CFI) was proposed with a electromagnetic field identified with a linear combination of isovector and isoscalar vector meson fields: $J_\mu^{em} = J_\mu^3 + \frac{1}{2}J_\mu^Y$, with eg. $J_\mu^3 = -\frac{m_\rho^2}{2\gamma_\rho}\rho_\mu$. An amplitude describing an interaction of a photon γ^* with virtuality q^2 with hadrons A, B is:

$$[\gamma^* A \rightarrow B] = -e \frac{m_\rho^2}{2\gamma_\rho} \frac{1}{q^2 - m_\rho^2} [\rho^0 A \rightarrow B] + (\omega, \phi)$$

via an interaction of the on-shell ρ, ω, ϕ states.

For elastic scattering $\gamma^* A \rightarrow A, \gamma^* B \rightarrow B$ one finds universality of the vector-meson coupling ($f_{\rho AA} = f_{\rho BB} = \dots = f_\rho$, where $f_\rho = 2\gamma_\rho$), arising from the universality of the electromagnetic coupling e . The coupling constant f_ρ has been measured in e^+e^- annihilation, in eg. the $\rho \rightarrow 2\pi$ channel, in Novosibirsk and Orsay operating since 1966/7.

According to CFI the electromagnetic field is due to vector mesons, therefore, eg.

$$\partial^\mu F_{\mu\nu}^3 = \frac{em_\rho^2}{2\gamma_\rho} \rho_\nu,$$

But what is a Lagrangian? The correct Lagrangian, consistent with gauge invariance,

were proposed by Kroll, Lee, Zumino in 1967:

$$L = -\frac{e}{2f_\rho} \rho_{\mu\nu} F^{\mu\nu} + \frac{e}{f_\rho} A_\mu J^{(\rho)\mu}$$

or

$$L' = \frac{e'}{2f_\rho} \rho'_\mu A'^\mu - \frac{1}{2} \left(\frac{e'}{f_\rho}\right)^2 m_\rho^2 A_\mu'^2,$$

with $e^2 = e'^2/(1 + e'^2/f_\rho^2)$, and similar linear relations between unprimed and primed fields. In such way mass of the photon is equal 0 and the photon propagator has at the lowest order two relevant contributions arising from two terms in the L' .

CFI predicted "hadronlike behavior of the photon", in particular a relation for amplitudes $A_{\gamma p \rightarrow \rho^0 p} = \frac{e}{2\gamma_\rho} A_{\rho^0 p \rightarrow \rho^0 p}$. A diffractive peak, typical for pure hadronic processes, was established for the vector meson photoproduction in 60-ties (XXc.) at DESY and SLAC.

It was in 1967 when Stodolski applying this vector meson dominance ideas to derive a sum rule combining the forward Compton-scattering cross-section for $\gamma p \rightarrow V p$ ($V = \rho, \omega, \phi$) and the total γp cross-section at high energy. However, to agree with $\sigma_{\gamma p}$ data about 20 % larger Compton contribution was required. It led to the notion of the Generalized Vector Dominance (GVD) model by Schildknecht, Sakurai (1972) with additional contribution of continuum massive vector states, which start to dominate for large virtuality of the photon.

In the same 1967 year the question was posted on the dependence on mass number A of the photon-nucleus interaction and then the answer was given (i.e. hadronlike behavior of the cross section $\approx A^{2/3}$) by Stodolsky. The further development of these ideas, together with a shadowing phenomena, led to a deep-inelastic scattering physics, with a treatment of vector mesons as quark-antiquark states.

Finally, it is worth mentioning here a low energy effective lagrangian approach introduced in early 80-ties (XXc.) [5], called a

Hidden Local Symmetry Lagrangian, where the vector mesons are treated as dynamical gauge bosons of a spontaneously broken hidden local symmetry. This model, with isospin breaking effects mostly from the ρ, ω, ϕ mixing, was used very recently [6] to describe properly both the pion formfactor data in the e^+e^- annihilation and in the τ decay. This is important for a reliable estimation of the vacuum polarization contribution for the $g - 2$ for a muon, see below.

2.2 Curve and photons

Less standard idea was presented at PHOTON 2005 by L. Stodolsky [7]. If the initial and final velocity of the radiating particle are the same there is no IR catastrophe and the number of photon radiated by a charge following a given curve is finite. This number can be used to characterize the curve, as it is shown in Figure 1, for a curve which number is $n=38.8$.

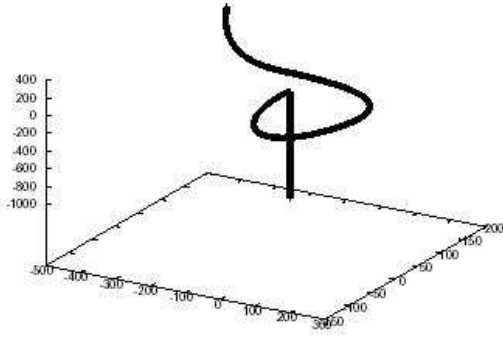


Figure 1: A curve which number is $n=38.8$.

3 Open problems

Here I will mention two new results, related to the photon-hadron interaction, which are relevant for a search for a new physics. They may help to close the for-long open problems. Then some old-new ideas related to the photons will be presented as well as the pho-

ton connection to the Higgs and Dark Matter physics.

3.1 Photons and hadrons

• *Hadronic contribution to $(g-2)_\mu$.* The hadronic contributions to the SM anomalous magnetic moment $(g-2)$ for the muon [8], the light-by-light (lbl) [9] and the vacuum polarisation, give the highest uncertainties in the SM result. Moreover, for the vacuum polarisation, where low-energy contribution has to be obtained using some experimental data, there is an discrepancy between the estimation based on the e^+e^- and on the τ -decay data, as presented in Figure 2 [10]. As more straightforward are the e^+e^- data, with a dominant contribution due to the $\pi\pi$ channel, recently only these data are being used to derive the SM prediction. However very recently it was shown [6] that the model based on the Hidden Local Symmetry Lagrangian [5], mentioned above, provides for a first time the consistent description of both the e^+e^- and the τ -dipion spectra. It confirms therefore $3.2-3.3 \sigma$ disagreement between the SM prediction and experimental data on anomalous magnetic moment for muon [11].

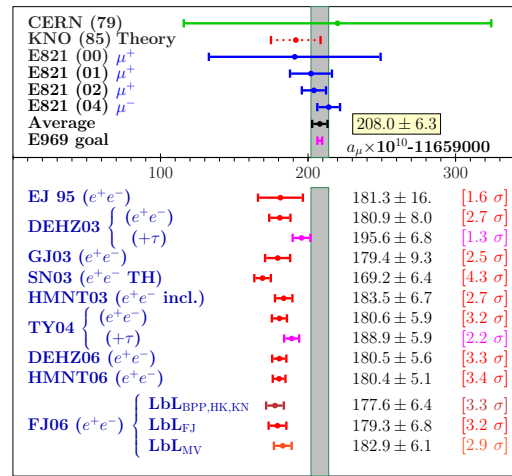


Figure 2: SM-prediction and data for a_μ [10].

• *Production of $b\bar{b}$ in $\gamma\gamma$ collision.* The new ALEPH [12] data on the production of the $b\bar{b}$ pairs in $\gamma\gamma$ collision show an agreement with QCD, in contradiction with three other LEP experiments. Here the b quarks were identified using lifetime information and the cross section for $\sqrt{s} = 130 - 209$ GeV was found to be $\sigma(e^+e^- \rightarrow e^+e^-b\bar{b}X) = (5.4 \pm 0.8(stat) \pm 0.8(syst))$ pb (NLO QCD prediction is 2.1 - 4.5 pb). The only other published LEP results on b -quark production in $\gamma\gamma$ collisions is by the L3 Collaboration, obtained from a fit to the transverse momentum of leptons with respect to jets. The cross section was measured to be about three times the prediction of NLO QCD and similar results have been reported at conferences by OPAL and DELPHI.

3.2 Light from the hidden sector

There is a very old but still actively tested idea, which appears in the extensions of SM, on a possible existence of a second species of photon which is uncoupled to known forms of matter - the *hidden* (sector) photons. In 1982 Okun proposed a para-photon model (other name *exphoton*)[13], with mixing of massive hidden photon with the ordinary photon. It appears in the QED if an extra U(1) symmetry is introduced, with the *para-photon* as a gauge boson and with a corresponding *para-charge*. Since in such models a very light charged scalar may appear and no such particle is observed, it is expected that the electric charge of this particle must be very small fraction of an electron electric charge (*mini-charge or milli-charge*) [15]. Similar model with oscillation of photons was considered in [14]. For hidden sector photons one can search for in the precision optical experiments, in particular light-shining-through-walls experiments [16]. Also the Super-Kamiokande [17] can be sensitive to the hidden sector photons as they can be produced through oscillation from the photons emitted by Sun. It is worth mentioning that

milli-charged particles may influence cosmic microwave background radiation [18]. It can offer the explanation of the galactic 511 keV line as coming from MeV milli-charged dark matter [19].

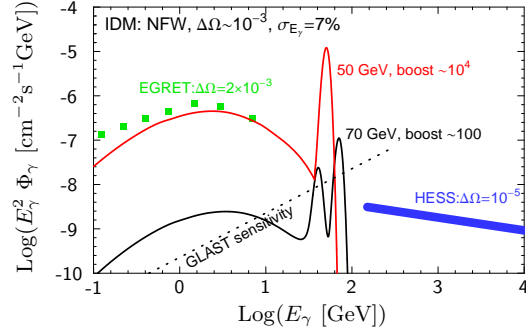


Figure 3: The energy spectrum of the photons from the annihilation $H_D H_D$ (mass 50 and 70 GeV) to the $\gamma\gamma$; the limits from EGRET and HESS and sensitivity from the GLAST experiments [25].

3.3 Photons, Higgs and dark matter

• *Photons and Higgs sector at colliders.* Photons play an important role in testing the Standard Model, in particular its Higgs sector. Higgs mechanism in this model relies on introducing one doublet of scalar fields and spontaneous EW symmetry breaking. As a result the W and Z gauge bosons become massive, while the photon remains massless. An existence of one spin-0 neutral Higgs particle h is predicted. According to the LEP data, its mass should be above 114.4 GeV. Neutral Higgs boson can couple with photons only via a loop with contribution from all charged particles of the theory. The unique property of this coupling is that heavy particles, which get masses from the Higgs mechanism, do not decouple.

In the simplest extension of the SM with two doublets of scalar fields (2HDM, MSSM) five Higgs bosons appear, two charged H^\pm and three neutral $h_{1,2,3}$. (In the CP-

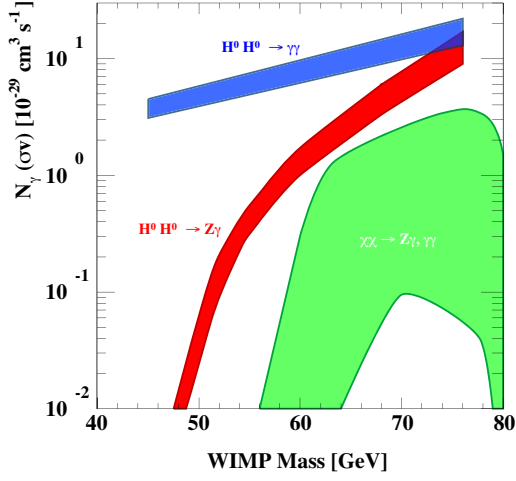


Figure 4: Comparison of the rate for annihilation of dark scalar $H_D H_D$ and neutralino $\chi\chi$ to the $\gamma\gamma, Z\gamma$ final states as a function of the mass of dark matter candidate [25].

conserving neutral scalar sector there are two CP-even Higgs bosons h, H and one CP-odd A . If CP is violated three neutral Higgs bosons h_i mix.) CP property or possible mixing of the neutral Higgs bosons can be tested in the $\gamma\gamma$ collisions. Also for charged Higgs bosons search photons can play crucial role due to their direct couplings.

At the LHC, the important channel for a search for a light SM-like Higgs boson is $gg \rightarrow Higgs \rightarrow \gamma\gamma$. Note, however that the intermediate mass Higgs-boson may decays into a photon and the unparticle [?](via a one-loop process) with the branching ratio compared with decay to two photons [21]. At the LHC there is also a possibility to produce Higgs boson in the $\gamma\gamma$ collision. However, such production process can be studied more precisely at the Photon Linear Collider (PLC), a possible option of the International Linear Collider (ILC) and of the CLIC, with the energy range 0.5-1 TeV and 3-4 TeV, respectively.

• *Significant γ -lines in Inert (Dark) 2HDM.* If to the SM-type scalar doublet ϕ_1 another scalar doublet with an odd Z_2 -parity (for Z_2 transformation $\phi_2 \rightarrow -\phi_2$) is added one gets the Z_2 -conserving Higgs sector only if ϕ_2 has zero vacuum expectation values (vev) and does not couple directly to the fermions. In such case Higgs sector consists of the additional with respect to h four Z_2 -odd scalars (H_D, A_D, H_D^\pm) and the lightest neutral one, eg. H_D , can be a good candidate for the Dark Matter. Such model, called the Inert (Dark) Doublet Model, was introduced by Deshpande and Ma in 1978 [22], later it was considered also by other authors, for example in [23, 24], both from point of view of particle physics and astrophysics. It was found that for the H_D mass between 40 and 80 GeV the correct cosmic abundance is obtained (WMAP).

In [25] possibility of a significant gamma lines from the annihilation $H_D H_D \rightarrow \gamma\gamma, Z\gamma$ was investigated. This loop-induced monochromatic γ production would be exceptionally strong, Figure 3. It was shown that these events would be ideal to search for in the upcoming GLAST experiment. Comparison of the rate for these events and for events with neutralino dark matter candidates is shown in Figure 4.

4 Photon Linear Collider - PLC

4.1 PLC - an option at ILC

The project called the International Linear Collider (ILC), corresponds to the planned e^+e^- collider with energy 0.5 - 1 TeV. It is described in detail in the ILC Reference Design Report [26] released in August 2007. The $\gamma\gamma$ and $e\gamma$ options, called in short the Photon Linear Collider (PLC), can be realized at the ILC by using backward Compton scattering of the electron beam on a laser light [27]. The PLC is not a part of the baseline ILC design and according to the David J. Miller, who has chaired the Gamma-Gamma

Planners (GGP) meeting during PLC2005, following issues need to be tackled in order to make PLC a reality: optical cavity, beam dump, luminosity maintenance, crossing angle, backgrounds. Also a list of "golden" processes [28] whose study will justify the PLC option needs to be reviewed.

In the PLC option both energy and polarization of the photon beams vary, since they are produced in the scattering process. One can choose polarization of the electron beam (for PLC only electron beams are needed) and laser light in such way to get monochromatic highly polarized photon beam. In particular one can have high luminosity $\gamma\gamma$ option corresponding to the high-energy peak ranging from 0.6 to 0.8 of the energy of the parent e^+e^- collision. In such option a resonance production of $C=+$ states (eg. Higgs boson) allows to make very precise determination of its properties. Both $\gamma\gamma$ and $e\gamma$ have higher mass reach than the corresponding e^+e^- collider, since here a single production is possible. High polarization of the beams (both circular and linear) allows to treat $\text{PLC}_{\gamma\gamma}$ as a CP filter, since two photons can form a $J_z = 0$ state, both with even and odd CP parities.

The physics potential of the PLC is very reach. It is an ideal observatory of the scalar sector of the SM and beyond, leading to important and in many cases complementary to the e^+e^- ILC case tests of the EW symmetry breaking mechanism. It is also best place to study hadronic interaction of the photon, both in $\gamma\gamma$ and $e\gamma$ options, for a really real (ie. not Weizsäcker-Williams) high-energy photons.

Independently whether at the LHC the SM-like Higgs scenario will be found or completely new phenomena will be discovered, PLC may be useful to clarify a picture.

4.2 9 good reasons to build a PLC

1. Precise measurement of the $h\gamma\gamma$ coupling. The s-channel resonance production of $C=+$

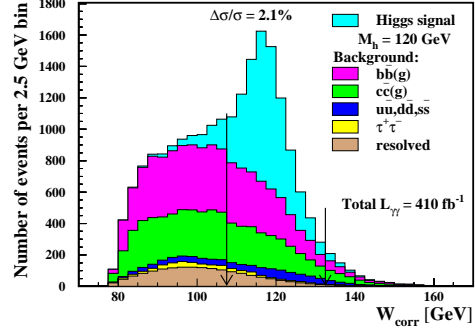


Figure 5: Distributions of the corrected invariant mass, W_{corr} , for selected $b\bar{b}$ events; contributions of the signal for $M_h = 120$ GeV and of the background processes [29].

particle allows to perform precise measurement of its properties. The precision of the cross-section measurement for the SM Higgs decaying into $b\bar{b}$ final state is between 2 to 3 % for mass 120-155 GeV (Figure 5) [29, 30]. By combining this production rate with the 1 % accuracy measurement of the $Br(h \rightarrow b\bar{b})$ at the e^+e^- ILC, the width $\Gamma(h \rightarrow \gamma\gamma)$ can be determined with accuracy 2 %, for mass of 120 GeV. This allows to discriminate even between the SM-like Higgs models. For mass range 200-350 GeV accuracy of the $\gamma\gamma \rightarrow WW$ cross-section measurement is still high: 3 - 8 %. Due to the interference with non-resonant background in WW/ZZ [31] and $t\bar{t}$ channels [32] it is possible to measure not only absolute value of the $h\gamma\gamma$ amplitude but also its phase.

2. Testing the Higgs-self coupling. Production in the $\gamma\gamma$ collision pairs of neutral Higgs bosons allows to test the trilinear Higgs couplings, necessary for a reconstruction of the Higgs potential. They can be measured for the Higgs-mass range 120-150 GeV at lower energies than at the e^+e^- ILC and with higher precision than at the LHC and ILC [33].

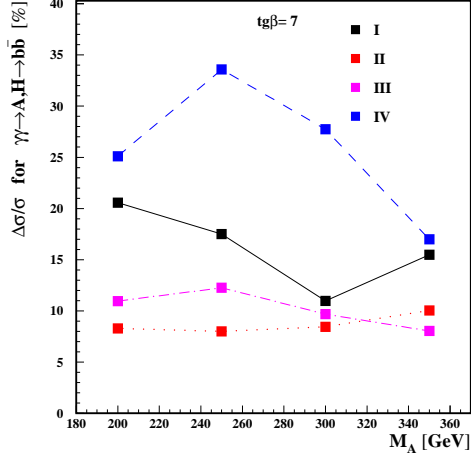


Figure 6: Precisions of $\sigma(\gamma\gamma \rightarrow A, H \rightarrow b\bar{b})$ measurement expected after one year of the $\text{PLC}_{\gamma\gamma}$ (TESLA) running, for $M_A = 200$ – 350 GeV, $\tan\beta = 7$ and four MSSM parameter sets [35].

3. Covering the LHC wedge. PLC can play important role in covering the so called LHC wedge, which appears for the MSSM for the intermediate $\tan\beta$. For these parameters LHC may not be able to discover other Higgs particles beside the lightest SM-like Higgs boson h . Also at the ILC (with CMS energy 500 GeV) it may not be possible, while $\text{PLC}_{\gamma\gamma}$ option of such collider an observation of heavy (degenerate) A and H bosons, with masses above 200 GeV, would be feasible (Figure 6) [34, 35, 36].

4. Testing CP properties. Testing the CP nature of the Higgs bosons can be performed at the PLC by using the initial polarization asymmetries and/or from the observation of decay products [37]. For the ZZ and WW decays channels the angular distribution of the secondary WW and ZZ decays products can be used [38]. In the $\gamma\gamma \rightarrow \text{Higgs} \rightarrow \tau\bar{\tau}/t\bar{t}$ one can perform a model independent study of the CP-violation, exploiting fermion po-

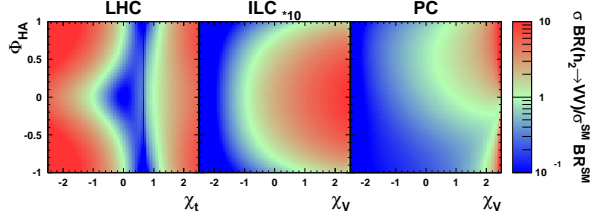


Figure 7: A determination of the relative couplings to $V = W/Z$ and t -quark as well as a CP mixing angle Φ_{HA} in the CP violating 2HDM at LHC, ILC and $\text{PLC}_{\gamma\gamma}$ [46].

larization [44, 32, 45]. Higgs formation in $\gamma\gamma$ collisions proves particularly interesting for observing effects of the H/A mixing [39] and for CPX scenario of MSSM [40, 41], in particular to look for the light CP-violating Higgs, which may escape discovery both at the LEP and LHC. It is feasible to perform H and A discrimination for the LHC wedge using linear polarization of the photons [42].

5. Production of heavy sfermions in $e\gamma$. The $e\gamma$ option of the PLC allows to study associated production of heavy sfermions and light charginos/neutralinos in a case when the e^+e^- ILC energy will be not high enough for the heavy sfermion pair production [43].

6. Complementarity to ILC and LHC. Due to different coupling combinations for the Higgs bosons or SUSY particles production precision measurements at pp , e^+e^- and $\gamma\gamma$ collisions give complementary information allowing to differentiate between various models. In Figure 7, a comparison of determination of the relative couplings to gauge bosons and top quark as well as the CP mixing parameter (angle Φ_{HA}) in the CP violating 2HDM at LHC, ILC and $\text{PLC}_{\gamma\gamma}$ [46] is presented.

7. Photon structure and QCD tests. By combining results of the dedicated $\gamma\gamma$ and $e\gamma$

measurements quark and gluon distributions in the photon can be precisely measured over the wide kinematic range. Also the measurement of the spin dependent structure functions of the photon is possible. The total cross section for $\gamma\gamma \rightarrow$ hadrons is of fundamental importance.

8. Anomalous W and t couplings. The cross sections for the $\gamma\gamma \rightarrow W^+W^-$ and $e^-\gamma \rightarrow \nu W^-$ processes are very high at PLC allowing to study the anomalous $WW\gamma$ coupling with accuracy similar to that in e^+e^- collider. At the $PLC_{\gamma\gamma}$ there is a large sensitivity for anomalous $t\bar{t}\gamma$ couplings, due to the 4th power dependence of it of the $t\bar{t}$ production rate. Note, that at e^+e^- ILC the couplings $\gamma t\bar{t}$ and $Zt\bar{t}$ enter together. The single t production at the $PLC_{e\gamma}$ is the best option to measure the Wtb coupling.

9. New physics in $\gamma\gamma \rightarrow \gamma\gamma/\gamma Z/ZZ$. Neutral gauge boson production, $\gamma\gamma \rightarrow \gamma\gamma/\gamma Z/ZZ$, which appear only at the one-loop level in the Standard Model, allows to derive strong constraints on new physics contributions [47, 48], especially if they rely on a direct coupling to photons like for unparticles. In the $\gamma\gamma \rightarrow \gamma\gamma$ [49, 50, 51] the peculiar phases associated with the unparticle propagator in the s-channel give rise to unusual patterns of interference with t- and u-channels. Large deviation from the SM results (which are symmetric in s, t and u) can be obtained at $PLC_{\gamma\gamma}(500)$ even for the cut-off scale 5 TeV.

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